# The Application of System Dynamics Modelling to System Safety Improvement: present use and future potential

Mohammed Ibrahim Shire[a], Gyuchan Thomas Jun[a], Stewart Robinson[b]

*Loughborough Design School, Loughborough University, Loughborough, UK*
*School of Business and Economics, Loughborough University, Loughborough, UK*

**Abstract**

System Dynamics has the potential to study the aspects of complex systems including its likely effect of modifications to structural and dynamic system properties that cannot be achieved with traditional approaches. This paper presents a review of literature addressing safety issues using system dynamics across safety-critical domains. Forty studies were included and classified based on a customised human factors safety taxonomy framework. The thematic analysis of the literature resulted in five themes: external factors, organisational influences, unsafe supervisions, preconditions for unsafe acts and unsafe acts. The findings suggest that using system dynamics can be a potential tool in improving safety. This can be achieved through improved decision-making by basing it on system analysis, analysing past behavioural events in a modelling structure to plan effective safety policies, as well as looking at a holistic approach when analysing accidents.

Key words: System Dynamics Modelling, Safety

## 1. Introduction

Understanding the mechanism of complex systems is a daunting task. Several existing methods used for examining the causal nature of events are unable to account for the non-linear interactions and feedback in complex systems because they are based on a linear paradigm. Equipment or humans are wrongly held responsible for any mishap when accidents are described sequentially in a system. Thus, learning how to prevent the reoccurrence of accidents becomes very difficult as opportunities for understanding the system mechanism are not utilized (Underwood et al., 2016). Unfortunately, majority of the tools used within safety-critical industries are based on these linear, sequential models of causality (e.g. Root Cause Analysis, Human Performance Enhancement System, and the Swiss Cheese Model). Nevertheless, there is an increasing awareness that the current tools are becoming ineffective due to the complex nature of the systems within which they are used (Marais et al., 2009; Svedung & Rasmussen, 2002; Leveson, 2004; Le Coze, 2005; Reiman and Oedewald, 2007; Rasmussen, 1997). Several accident models based on a System Safety paradigm have been developed to address these challenges since linear and sequential tools are only suitable for industries with loose coupling and linear interactions (Hollnagel, 2008). Some of the models that adopt this System Safety paradigm include AcciMap (Svedung and Rasmussen, 2002), Functional Resonance Accident Model (Hollnagel and Goteman, 2004) and the Systems Theoretic Accident Model and Process (STAMP) (Leveson, 2004). Although they have a limitation in predicting system responses to policy changes, these models have been shown to be effective in analysing accident occurrence in complex socio-technical systems (Nancy Leveson et al., 2003). Whilst some policy decisions appear not to have any effect on safety, they might drastically reduce safety in reality as well as increase risk.

Various aspects of complex systems such as the possible effect of changes in the dynamic and structural system properties cannot be understood using traditional approaches but can be studied with System Dynamics (SD). Organisations can be better prepared for accidental occurrences if they are able to analyse the causal structure and dynamics behind such events as well as learn from them, which makes it more easy to comprehend the warning signs (events and behaviours) for accidents and errors. These warning signs may appear as frequent patterns of behaviour or structure that precedes an event. Several authors such as Wolstenholme (2003) and Senge (1990) have identified these common patterns and behaviours or system archetypes in different contexts.

SD is a computer-based simulation method primarily used for qualitative and quantitative analysis of complex problems that develop or persist over time. It has been widely used in modelling across a range of applications that range from socio-economic to engineering systems, but its potential has not yet been fully realised as a tool for understanding system safety and supporting important strategic decision-making. The objective of this paper is to examine the connection between safety improvement and SD by reviewing literature that attempts to improve system safety in complex systems by utilising SD modelling. In doing so, the following three questions are explored: what safety issues have been addressed by SD, how has SD been applied to improve system safety and how might SD be further applied to system safety?

The rest of the paper is organised as follows: the second section will briefly look at the concept of system safety with a clear emphasis on the evolution of existing system safety tools and its present limitations. The third section will briefly explain what SD is. The fourth section will describe the safety framework used to compartmentalise and analyse the findings from the literature analysis and the approach to the literature review. Findings are presented in section five, and finally, we return to discuss our findings with respect to the three research questions.

## 2. System Safety in Complex Socio-Technical Systems

Earlier types of accident models (sequential and epidemiological) have viewed safety in a reactive way as opposed to a proactive manner by primarily focusing on retrospectively ‘learning from events’ instead on proactively assessing the safety (Hollnagel et al., 2007). This ‘learning from events’ strategy has obviously pointed out several faults in a large number of past accidents, which has further emphasised the need to address safety proactively as well as to focus on organisational processes that are involved in ‘safety management’. As a result, systemic models have been introduced in a bid to carry out a more detailed investigation on managerial and organisational failures in connection with the occurrence of accidents (Reason, 1990). There are two basic concepts used in existing literature on system safety, and these include the notion that safety is a ‘control problem and that a ‘system theoretic’ approach is required to address safety (Saleh et al., 2010). Safety is regarded as a control problem since accidents occur whenever the management control system cannot sufficiently handle component failures, external troubles and deteriorating interactions.

Today, accident occurrence is still largely being attributed to human error. Incentives exist for organisations to blame operators to evade or avoid possible lawsuits and public outcry. According to Johnson (1980), an accident is more likely to be attributed to human error when less is known about the specific circumstances. Perrow (1999, 1984) said that “human error” is usually the only reasonable explanation given by organisations for accidents whose real cause is either complex or uncertain or plainly embarrassing. The truth is that accidents are not usually caused by humans because they are always governed by a set of rules and behaviour which determines how they interact within a social and physical context. Thus, it is easy for an organisation to detect any form of deviation with such rules and behaviour in place.

Rasmussen and Svedung (2002, 2000) attributed the Zeebrugge ferry accident to those in charge for making decisions about scheduling and operation, vessel and harbour design as well as cargo and passenger management because they failed to understand the impact of their decisions on the system-level processes and other decision makers. Rasmussen (1997) stated that most decisions are affected by budget pressures, time and short-term contextual incentives which affect behaviour, and they are only locally rational. Although these decisions may seem safe and reasonable within the individual work environment and local pressures, they may interact in unexpected ways to create accidents when considered in relation to the entire system operation (Dulac and Leveson, 2004).

The actual cause of accidents in complex socio-technical systems is poor decision making, which is often due to poor safety culture or excessive performance pressure. As a result, unknown failure modes are usually not the cause of accidents in such systems. Thus, in order to carry out an effective risk analysis, a more inclusive approach is required which encompasses the managerial, technical, organisational, political and social aspects of the system and its environment. Complex systems often become unstable or unsafe when accidents occur in such systems, which may lead to catastrophes whenever there are small deviations (Leveson, 1995; Leveson, 2004; Rasmussen, 1997). Thus, it is important to keep risk at a sustainable level throughout the lifecycle of the system in order to avoid the occurrence of accidents.

### *2.1. Systemic Accident Models*

The occurrence of accidents in complex socio-technical systems has been analysed using several systems techniques. Whilst individual-centred approaches were used in the late 1970s to find the causes of accidents; the systems approach to safety became popular in the 1980s as it was observed that disasters were primarily caused by managerial failures (Salmon et al., 2010). Up to now, several risk analysis methods have emerged that dominate system safety literature such as the Risk Management Framework (Rasmussen, 1997), Human Factors Analysis and Classification System (Shappel and Wiegmann, 2000), Functional Resonance Analysis Method (Hollnagel and Goteman, 2004) and STAMP (Leveson, 2004). These non-linear methods have been very effective in investigating the complex interactions amongst systemic factors that may lead to accidents.

- Risk Management Framework was introduced by Rasmussen wherein he developed multi-levels to explain the complexity of a socio-technical system involved in the control of safety. Rasmussen observed that the dynamic character of today's society dramatically changed the types of methods needed to understand structure and behaviour of socio-technical systems. Factors such as high degree of coupling of technologies, the volatility of economic and political climates and a fast-moving technological change each contribute to an environment in which pressures and constraints that define work practices are continuously shifting (Vicente and Christoffersen, 2006). Consequently, to fully appreciate why such systems fail or work, modelling tools are required that provide an integrated view of various factors that directly and indirectly input on complex socio-technical systems. Here, the complex socio-technical systems involved in risk management generally consist of five levels including government, regulators and associations, company, management, and staff and work.
- HFACS was developed by Shappell and Wiegmann (2000) based on sound human error theory. It recognises all the holes in Reason’s (1990) famous Swiss cheese model. It includes the following four levels; unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences. Each tier is broken down into yet lower sub-tiers. At the lowest level are the definitions utilised to categorise and classify the identified causal and contributing factors (Leplat and Rasmussen, 1984). It was primarily developed to investigate accidents/mishaps in the aviation sector; however, it has been adapted to a range of industrial domains, e.g. maritime and railway.
- FRAM was introduced by Hollnagel to capture emergent phenomena in complex nonlinear systems (Hollnagel & Goteman, 2004). The concept behind this risk analysis method is that accidents occur in a system due to unforeseen resonances between the system and typical noise in its environment. Because this model focuses on system designs which are resistant to noise and disturbance, it is

suitable for accident prevention. In addition, an analysis is performed on the system to detect resonance modes which may be created through actions. Whilst this method does not take the linear-event chain into consideration; it recognises the fact that safety is an emergent system property. Moreover, it places importance on the very real problem of the unexpected effects of disturbances on system operation.

- STAMP was introduced by Leveson as a new causality model based on systems control theory. STAMP is not based on the premise of a chain of events, but rather is a constraint-based model that focuses on the important interactions between system components (Leveson, 2004, 2003). Whilst safety is considered to be a control problem; hazards are referred to as system states which lead to accidental events when merged with certain conditions in the system environment. Hierarchical control structures, which cover the whole socio-technical system, should be employed throughout the lifetime of the system in order to enforce constraints on the system states. In this hierarchical control structure, every level receives feedback from the level below it since all levels impose control on the levels below them. Military defence, aerospace, chemical, energy and transportation systems, as well as health, are some of the fields in which this structure has been used.

All these approaches have limitations. The Risk Management Framework suffers from analysts' hindsight leading to potential oversimplified causality, and counterfactual reasoning (Dekker, 2002) and its approach can only be used retrospectively. HFACS suffers from forceful 'fitting' of data into categories provided by the analyst which makes validation difficult (Salmon et al., 2005). FRAM does not provide the ability or instruction for how to discover resonance modes within the system or address system migration to high-risk operations (Stringfellow, 2010) and heavily relies on expert judgement in assessing system variability. Several authors have employed STAMP in conjunction with SD to investigate the causes of the control failures identified, however, it requires significant accurate data and becomes less useful when used for the analysis of smaller scale accidents as data required is often not readily available (Salmon, 2011). For SD to be used as a step in the STAMP process, several steps have to be implemented as a requisite. Furthermore, a STAMP analysis does not incorporate a timeline as the control structure diagram represents a 'snapshot' of the system's dynamic control relationships and organisational constraints (Johnson and Almeida, 2008). The aforementioned approaches may increase the system and risk understanding, but lack adequately supporting the decision-making on dynamic risk issues (Bjerga et al., 2016) and SD has the potential to addresses these limitations.

## 3. System Dynamics

SD is an analytical modelling approach for studying complex feedback systems (Forrester, 1961). The approach has two key aspects, namely qualitative and quantitative. The qualitative aspect, known as Causal-Loop Diagram (CLD), is a diagramming approach that maps the causal relationships between pairs of elements within a system and recognises feedback loops revealing types of system behaviour. These loops can either be balancing (goal-seeking) or reinforcing (vicious) cycle and can demonstrate unintended consequences of their interactions as illustrated in Figure 1 (dispensing errors in a pharmacy setting).

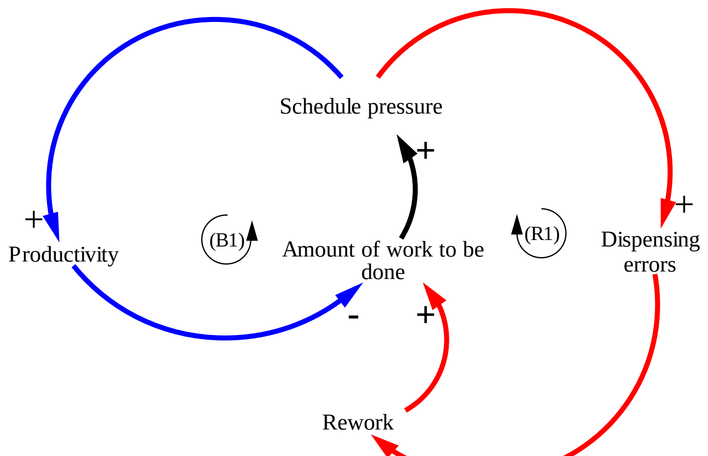

**Fig. 1.** Causal Loop Diagram of dispensing errors: an increase in schedule pressure leads to higher dispensing errors, more rework (re-dispense medications), increased amount of work to be done and back to even higher schedule pressure (reinforcing loop); an increase in schedule pressure, on the other hand, leads to increased productivity (faster work) decreased amount of work to be done and decreased schedule pressure (balancing loop)

The quantitative aspect is based on a stock-and-flow diagram which models the relationships using differential equations. Inflows and outflows alter stocks (the state of the system) and generate information upon which decisions and actions are based on. Figure 2 illustrates an example of a stock-and-flow diagram based on Figure 1.

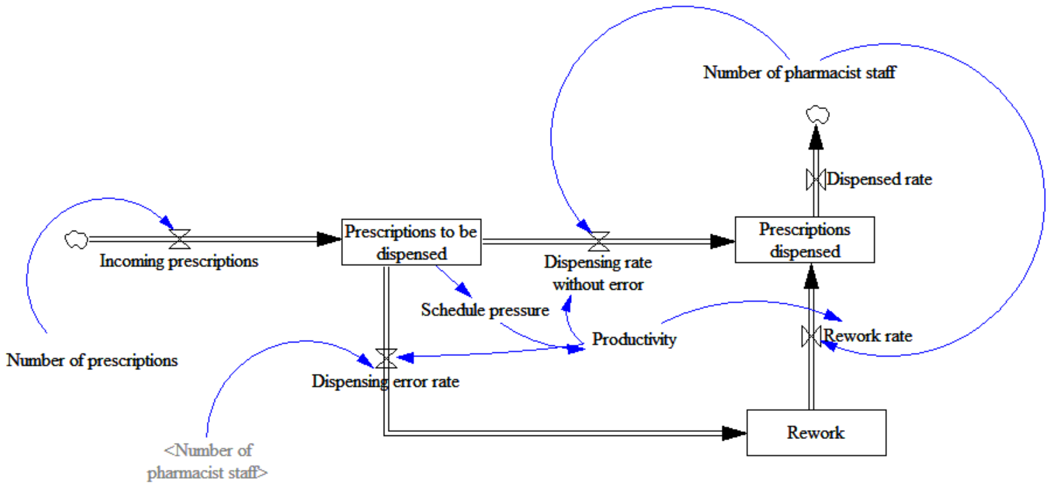


**Fig. 2.** Stock and Flow Diagram of dispensed prescriptions: an inflow is incoming prescriptions; an outflow is dispensing rate; a stock is the accumulation of prescriptions that are ready to be dispensed.

Decision makers are usually faced with the challenge of how to avoid using generalised notions about systems so as to utilise tools and processes that will enable them to have a better understanding of the complexity. This challenge can be addressed by using SD as it helps to enhance learning in complex systems (Leopold, 2016). However, learning about complex dynamic systems requires more than just creating mathematical models using technical tools. SD has a lot of advantages one of which includes providing a strong and transparent model structure which promotes collaboration between stakeholders and SD modellers in the case of participatory or group modelling (Anderson & Johnson, 1997)

Regarding safety, SD has the potential to provide stakeholders with the complex safety dynamics understanding of various contributing factors to errors and accidents and identify and test effective safety measures as described below. SD can address the limitations that other approaches have. The Risk Management Framework’s limitation of retrospective usage is addressed by SD as it can be applied both retrospectively to accident analysis and predictively to risk assessment. SD can address HFACS' limitation of forceful fitting of data into fixed categories by giving the modeller the unlimited restriction to accurately define categories. SD can address FRAM's reliance on expert judgement by presenting complex models in easy to understand visual context. STAMP’s limitation of requiring data at the multiple levels can be addressed by SD’s qualitative aspect which provides insight into the problem's structure in a selected boundary without requiring much data at the whole system levels; successful quantified models in SD can be built based on the availability of limited data (Ortiz et al., 2008). Finally, the uncertainty modelling which cannot be addressed by the aforementioned approaches can be addressed by SD’s traditional process such as sensitivity analysis and testing and by means of qualitative mode of behaviour interpretations (Pruyt, 2014; Walker et al., 2014).

In order to examine how has SD modelling approach been utilised to improve system safety in complex systems, the relevant literature was systematically searched, reviewed and analysed through the method described in the next chapter.

## 4. Method

A systematic approach was employed to identify literature based on SD and safety. There were no time limits placed on the search, as there is no previous systematic review in this area and the scope of available literature was unknown. The accessed databases were PubMed, Web of Science, Science Direct and Google Scholar databases. The search words used were: system dynamics, causal loop diagrams, stock and flow, all in combination with safety, safety management, accident, errors. The keywords were used in Boolean combination, joined by AND. Papers eligible for inclusion were those that described applications of SD modelling to support safety. The literature was further supplemented by relevant publications in the reference lists of the publications collected. The title and abstract of each study were read, and the full-text article obtained if the researchers found that the study applied to the research question, based on previous literature.

We used the most general definition of safety as being free from something undesired, unwanted or unacceptable (ISO/IEC, 2014) although it carries a plethora of definitions. Empirical research articles, review articles, academic book chapters and conference papers addressing safety improvement using SD approach, were selected for the study. We have also included papers that significantly employed SD as part of hybrid approaches with some other methods.

Both qualitative and quantitative SD approaches were included. The literature was analysed using thematic analysis (Braun and Clarke, 2006; Howitt and Cramer, 2008), which allows for the identification and exploration of major themes across the literature in a systematic, theoretically flexible manner. The initial stage of analysis involved becoming familiar with the literature by simply reading the articles. A total of 63 articles were finally identified that applied SD modelling to safety.

In order to examine what safety issues have been addressed by SD in the literature, the HFACS framework was chosen and used to identify and classify the SD applications. The HFACS framework comes equipped with its taxonomy to classify and analyses human error and accident causations. It has been validated through a number of studies across different industries such as military (Jennings, 2008; O’Connor et al., 2010; Shappell and Wiegmann, 2001), aviation (Reinach and Viale, 2006; Shappell and Wiegmann, 2001), rail (Baysari et al., 2008; Reinach and Viale, 2006), maritime shipping (Celik and Cebi, 2009), mining (Patterson and Shappell, 2010), Petroleum/Gas (Aas, 2008), construction (Garrett and Teizer, 2009) and healthcare (ElBardissi et al., 2007). The original HFACS framework describes 19 causal categories within Reason's four levels of human failure (Shappell and Wiegmann, 2000), but it lacks a crucial tier that is equivalent to the government tier in Rasmussen’s (1997) six-levels of risk management framework. Whilst useful as originally designed for aviation, the four levels lacked an essential level to encompass a number of industries. This study introduced a new tier, therefore, changing the original HFACS framework into a modified HFACS framework which is entitled HFACS-EE (External Extension). As presented in Table 5, changes include adding a layer of Rasmussen’s hierarchical taxonomy to the existing HFACS with an addition of a new tier called External Factors. The additional tier allows us to categorise the SD safety applications in their respective safety category. The thematic content of each paper is classified according to its primary foci (highlighted in dark grey) and its secondary foci (highlighted in light grey). Primary foci are identified as the strong themes of the paper, whilst secondary foci are identified as visible, but not central themes in the papers.

## 5. Results

Figure 3 shows the number of relevant articles published in each year from 1984 till 2016. It shows that the application of SD to safety started in the academic field in the early 1980s. Since then, a stagnation of no contribution has characterised its trend until 2002 when the number of published articles using SD for safety research increased to around three articles per year. The reasons for the early gap can be explained by the re-emergence of the sociotechnical approach based on complex non-linear models in the 1980s and beyond (Hettinger et al., 2015). In 2000, SD was recognised and proven to be a potent method to gain valuable insights into events of dynamic complexity and policy resistance (Sterman, 2000). In 2015 and 2016, safety applications using SD increased dramatically, generating significant interest.

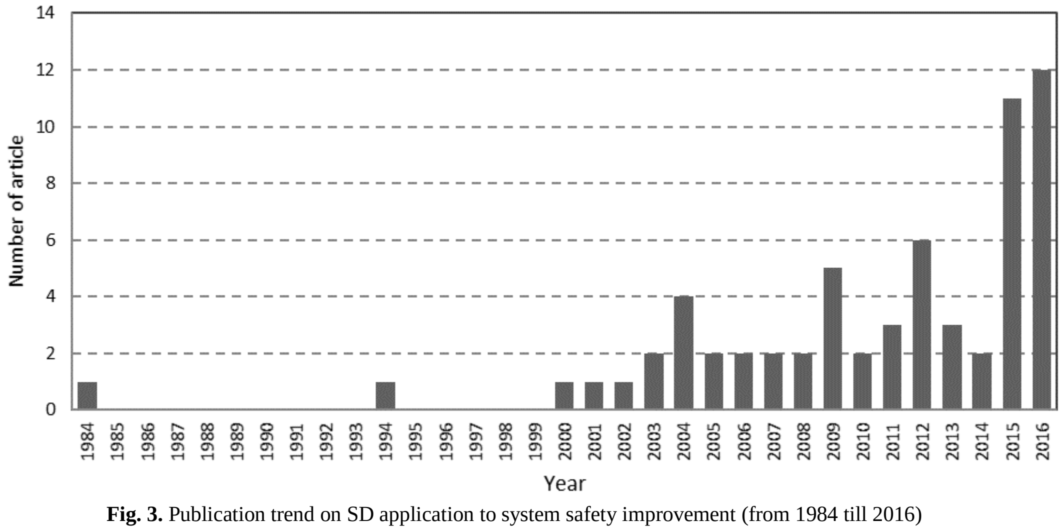


**Fig. 3.** Publication trend on SD application to system safety improvement (from 1984 till 2016)

The next four tables (Table 1-4) summarise SD applications by sector, model type, study type and HFACS framework. Table 1 illustrates that the most applied sector is healthcare (25%), then construction (13%) followed equally (10%) by three sectors (disaster, aviation, and traffic).

**Table 1** SD applications to safety by sector

| **Sector** | Healthcare | Construction | Disaster | Aviation | Traffic | Others |
|---|---|---|---|---|---|---|
| **Percentage** | 25% | 13% | 10% | 10% | 10% | 32% |

Table 2 shows that the majority of the applications (78%) used stock flow diagrams, which investigate system behaviours through quantitative models based on real-world data. On the other hand, there were still 22% of the applications that used only causal loop diagrams (qualitative model).

**Table 2** SD applications to safety by model type

| **Model type** | Quantitative model | Both models | Qualitative model |
|---|---|---|---|
| **Percentage** | 37% | 41% | 22% |

Table 3 shows that there are three main perspectives (i.e. theory development, problem-solving and case study) that altogether represent 90% of the identified papers. The remaining part is made up of methodological development. To contextually define the types of studies, a case study is an empirical inquiry using SD approach that investigates a contemporary phenomenon within its real-life context. Theory development is the application of SD approach for a given undertaken issue, analyse them technically with respect to current theory in order to gain carefully considered conclusions. Policy analysis and problem-solving is the use of SD approach using inquiry and arguments to produce and transform policy-relevant information that may be utilised in organisational settings to resolve policy problems. Methodological development is the application of SD is the use of SD approach using inquiry and arguments to produce and transform policy-relevant information that may be utilised in organisational settings to resolve policy problems. Methodological development is the application of SD modelling approach in areas not utilised before, leading to a significant contribution the development of SD methodology.

**Table 3** SD applications to safety by study type

| **Study type** | Case Study | Policy analysis/ problem solving | Theory development | Methodological development |
|---|---|---|---|---|
| **Percentage** | 43% | 33% | 14% | 10% |

Table 4 shows the categorisation results based on the extended HFACS taxonomy framework. Around 46% of SD applications focused on issues at the level of organisational influences, in particular, covering the areas concerning resource management, organisational climate and operational process. The second most identified articles were geared towards issues at the work level (29%) whilst issues at management level were the third highest (11%). External factors were the second lowest (9%) which is relatively low given that exogenous factors influence safety all the time. Unsafe acts were the lowest (5%) revealing a gap in trend as SD is mostly utilised for organisational interventions in order to improve the efficacy of enacted policies (Snabe, 2007).

**Table 4** SD applications to safety by HFACS framework

| **Taxonomy** | Organisational influences | Preconditions for Unsafe Acts | Unsafe Supervisions | External Factors | Unsafe Acts |
|---|---|---|---|---|---|
| **Percentage** | 46% | 29% | 11% | 9% | 5% |

Table 5 presents the overall summary of the detailed HFACS framework-based categorisation of the sixty-three articles identified. It shows what each article has addressed aspects of the safety (based on the extended HFACS framework). More detailed analysis for each category are presented in the following sections (5.1 – 5.4).

**Table 5** SD applications to safety by the extended HFACS framework– see Appendix A for the detail descriptions of the framework

Primary

Secondary

| | External Factors | | Organisational Influences | | | Unsafe Supervisions | | | | Precondition for Unsafe Acts | | | | | | | Unsafe Acts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Environmental Factors | | Condition of Operators | | | Personnel Factors | | Human Errors | | | Human Violations | |
| Papers | Regulatory | Others | Resource Management | Organisational Climate | Organisational Process | Inadequate Supervision | Planned Inappropriate Operations | Failure to Correct Problem | Supervisory Violations | Physical Factors | Technical Factors | Adverse mental State | Adverse Physiological State | Physical/Mental Limitation | Crew Resource | Personal Readiness | Skill-Based Errors | Perceptual Errors | Decision Errors | Routine Violations | Exceptional Errors |
| Homer, J.B., 1984 | | | | | | S | | | | | | P | | | | | | | | | |
| Anderson & Anderson, 1994 | | | P | | S | | | | | | | | | | | | | | | | |
| Lane, D.C., et al., 2000 | | S | S | | P | | | | | | | | | | | | | | | | |
| Oliva, R., 2001 | | | | | | | | | | | | P | S | S | S | | | | | | |
| Rudolph, J.W. & Repenning, N.P., 2002 | | | | P | S | S | | | | | | | | | | | | | | | |
| Cooke, D.L., 2003 | | | S | | | P | S | S | S | | | | | | | | | | | | |
| Mehmood, A., et al., 2003 | | | | | | | | | | | P | S | | | | | | | | | |
| Ellis, B.Y.R.E., 2004 | | P | | | | | | | | | | | | | | | | | | | |
| Lattimer, V. et al., 2004 | | S | | | P | | | | | | | | | | | | | | | | |
| Taylor, K. & Dangerfield, B., 2004 | | | | P | S | | | | | | | | | | | | | | | | |
| Tengs, et al., 2004 | | P | S | | | | | | | | | | | | | | | | | | |
| McDonnell, G., 2005 | | | | S | S | | | | S | | S | P | | | | | S | S | S | | |
| Simonovic, S.P. & Ahmad, S., 2005 | | | | | | P | | | | | | | | | | | | | | | |
| Cooke, D.L. & Rohleder, T.R., 2006 | | | | P | | | | S | | | | | | | | | | | | | |
| Salge, M. & Milling, P.M., 2006 | | | | | | P | | | | | | | | | | | | | | | |
| Ahmad, et al., 2007 | | P | S | | | | | | | | | | | | | | | | | | |
| Tang, Z., 2007 | | | | P | | | S | S | S | | | | | | | | | | | | |
| Ulrey, M. & Shakarian, A., 2008 | | | | P | S | | | | | | | | | | | | | | | | |
| Zhang, et al., 2008 | | | | | | | | | | P | S | | | | | S | S | S | S | | |
| Carhart, N.J., 2009 | | | | | | | | | | | | S | | | P | | | | | | |
| Minami, N. a. & Madnick, S., 2009 | | | | | | P | S | S | S | | S | | | | S | | | | | | |
| Mohaghegh, Z. et al., 2009 | | | | S | P | | | | | S | S | | | | | | | | | | |
| Topolšek, D. & Lipičnik, M., 2009 | | | | P | S | | | | | | | | | | | | | | | | |
| Xian-gong, L., et al., 2009 | | | | P | | S | | | | | | | | | | | | | | | |
| Morris, A., et al., 2010 | | | | | | | | | | | | P | S | | | | | | | | |
| Xiao-yan, W.X.W. & Jian-hua, Z.J.Z., 2010 | | | P | | S | | S | | | | | | | | | | | | | | |
| Kontogiannis, T., 2011 | | | | | | | | | | | | | | | | | P | S | S | | |
| Min, P. & Hong, C., 2011 | | | | | S | | P | | | | | | | | S | | | | | | |
| Mohamed, S. & Chinda, T., 2011 | | | | P | | | | | | | | | | S | | | | | | | |
| Goh, Y.M., et al., 2012a | | | | P | S | | | | | | | | | | | | | | | | |
| Goh, Y.M., et al., 2012b | | | | P | | | | S | S | | | | | | | | | S | | | |
| Goh, Y.M., et al., 2012c | | | | P | S | | | | | | | | | | | | | | | | |
| Leveson, et al., 2012 | P | | S | | | | | | | | | | | | | | | | | | |
| Wei, Z. et al., 2012 | | | | | | | | | | | S | | | | P | | S | S | S | S | |
| Wu, Q. & Xie, K., 2012 | | | | S | | P | | | | | | | | | | | | | | | |
| Bouloiz, H. et al., 2013 | | | | P | | | | | | | | | | | | | | | | | |
| Guo, S., et al., 2013 | | | | | | | | | | | | P | | S | | | S | | | | |
| Wang, J.Y.H. et al., 2013 | | P | | S | | | | | | | | | | | | | | | | | |
| Han, S. et al., 2014 | | | S | | | | | | | | | | | P | S | | | | | | |
| Shin, M. et al., 2014 | | | | | | | | | | | | P | S | | | | | | | | |
| Chia, E. et al., 2015 | | S | P | S | S | | | | | | | | | | | | | | | | |
| Chong, M. et al., 2015 | | | | | | | | | | P | S | | | | | | | | | | |
| Du, H. & Zhang, Q., 2015 | | | S | S | P | | | | | | | | | | | | | | | | |
| Guo, B. et al., 2015 | | | S | P | S | | | | | | | | | | | | | | | | |
| Jiang, Z. et al., 2015 | | | | S | | | | | S | | | | | | | | P | | | S | |
| Maryani, A. et al., 2015 | | | P | S | S | | | | | | | | | | | | | | | | |
| McClure, R. et al., 2015 | S | S | S | P | S | | | | | | | | | | | | | | | | |
| Nakamura, M. et al., 2015 | | | | | | | | | | | | | | | | | P | S | S | S | S |
| Orjuela, J. et al., 2015 | | S | S | P | S | | | | | | | | | | | | | | | | |
| Rashwan, W. & Arisha, A., 2015 | | | | | | | | | | | | P | S | S | S | S | | | | | |
| Woo, T., 2015 | | | S | | S | | | | | S | P | | | | | | | | | | |
| Akkermans, H. & Van Oorschot, K., 2016 | | | S | S | S | S | P | S | | | | | | | | | | | | | |
| Da, X. 2016 | | | | | | | | | | | | P | S | S | | | | | | | |
| Garbolino, E. et al., 2016 | | | S | P | S | | | | | S | S | | | | | | | | | | |
| Goh, Y. & Askar Ali, M., 2016 | | | S | P | S | | | | | | | | | | | | | | | | |
| Gonzalez, J. et al., 2016 | | | S | S | P | | | | | | | | | | | | | | | | |
| Koh, Y. et al., 2016 | | | | | | | S | | | S | P | | | | | | | | | | |
| Lu, Y. et al., 2016 | | | S | P | S | | | | | | | | | | | | | | | | |
| Macmillan, A. et al., 2016 | S | P | | | | | | | | | | | | | | | | | | | |
| Rong, H. et al., 2016 | | | S | S | S | | | | | S | P | | | | | | | | | | |
| Turner, T. et al., 2016 | | | P | S | S | | | | | | | | | | | | | | | | |
| Wang, F. et al., 2016 | | | | P | S | S | | | | | | | | | | | | | | | |
| Yan, W. et al., 2016 | | | | | | | | | | P | S | S | S | S | | | | | | | |

*5.1. External factors*

Six SD applications have been identified and constructed that have the potential to impact safety policy from *external factors* (see Table 6). They include *regulatory, social, political, environmental, and economic influences*. The first five papers in Table 6 look at external factors resulting from economic pressure, environmental concerns and legal pressure whilst the last paper looks at regulatory factors. A large portion of the cited applications (66%) applied conceptual modelling (Causal Loop diagrams) to investigate ways to improve public health and safety.

Looking at the *regulatory influences*, a combination of STAMP and SD models was applied by Leveson et al. (2012) to improve pharmaceutical safety by enhancing the safety of current drugs as well as encouraging the development of new drugs. They combined several SD conceptual models to investigate the potential effectiveness and unintended side effects of FDA's post-approval safety policies. Authors identified additional safety controls that could be incorporated in the FDA legislation to improve public safety. Wang et al. (2013) address the rise in demand for PTSD services in military veterans by evaluating the screening and referral processes of the American Veterans Health Administration. Using a conceptual diagram, they include organisational factors and individual factors from pre-enlistment to post-discharge in their analysis of PTSD prevention and treatment. Ellis (2004) developed an SD conceptual model of the Colombian civil war based on the interactions amongst criminal organisations, the guerrilla organisations, the economic base of the Colombian society and its government. From the model analysis, it was observed that the large number of "reinforcing feedback effects" in the system was capable of instigating violence and social chaos across the region, which could hamper the governments' ability to react faster to narco-terrorism and other regional phenomena than traditional analysis.

**Table 6 1**Literature Review – External Factors

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Ellis | 2004 | Case study | Causal Loop diagram | Drug and Terrorism (Public safety) | To present a systemic analysis of the geopolitical implication of narcoterrorism dynamics in Colombia and the Andean Ridge region and how this can affect public safety in the wider region. |
| Tengs et al. | 2004 | Theory Development | Stock-and-Flow diagram | Healthcare (Public Health Safety) | To analyse gains or losses within public health from any change in the hazards or patterns of cigarette use |
| Ahmad et al. | 2007 | Case Study | Stock-and-Flow diagram | Healthcare (Public Health Safety) | To compare the health benefits to society when various levels of tax increase are introduced as well as preventing youth access to cigarettes by increasing the legal purchase age to 21 |
| Leveson et al. | 2012 | Case study | Causal Loop diagram | Healthcare (Public Health Safety) | To evaluate the efficacy of the safety policies when new pharmaceutical drugs are introduced. |

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|---|---|---|---|---|---|
| Wang et al. | 2013 | Case study | Causal Loop diagram | Military & Healthcare (Patient Safety) | To analyse the cost and benefit of the U.S. Military psychological health system on public safety |
| Macmillan et al. | 2016 | Case study | Causal Loop diagram | Traffic Safety | To analyse media's reports when it comes to cyclist mortality rate in London, concluding that increases in reporting driven by greater participation potentially give the impression that cycling has become more dangerous, and in turn may prevent further increases in participation. |

### *5.2. Organisational influences*

Twenty-nine SD applications have been identified and developed that have the potential to impact safety policy at the *organisation level*. They include *organisational climate, resource management and operational process*.

#### *5.2.1 Organisational climate*

Nineteen papers utilised SD applications that address the *organisational climate* which looks at the organisational culture, policies and structure (see Table 7). A vast majority of the papers utilised both a conceptual model and a simulation model to promote effective group learning.  This is shown in Cooke et al. (2006) who modelled the organisational memory of lessons learned from past accidents. In order to combat organisational complacency in safety and promote effective learning, the Perrow's Normal Accident Theory (Perrow, 1984) and High-Reliability Theory (Rochlin, 2007) were combined by the researchers to model an organisational response system in which safety-related or past events were used as the basis for future planning. In their models, safety-related variables such as safety commitment, unsafe acts and production pressure were used to illustrate a bigger picture for future learning. Similarly, Xian et al. (2009) and Li et al. (2009) analysed fatal gas accidents in coal mines in China. Their simulation results revealed that time delay and feedback should be part of China's coal mine safety organisational decision-making. Goh et al. (2012b) study revealed that risk perception could deteriorate when management had *a strong production focus*. Also, by using a group model building approach, Goh et al. (2012c) attempt to understand the reasons why even if the organisation had invested a mass of resources into safety, the injury rate could not be decreased.  McClure et al. (2015) developed an SD safety model that reveals the unintended consequences as well as opposing of health policies and interventions. By explicitly including both positive (increased active transport) and negative (increased transport injuries and fatalities) potential effects of land-use and transport policies, the authors were able to assess the overall benefits of different policies for population health. Guo et al. (2015) created an SD model and applied system archetypes to construction of safety management. They identified eight archetypes, ranging from "workers' conflict goals" to "blame on workers" or "reactive and proactive learning".

**Table 7 2**Literature Review – Organisational Climate

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Rudolph and Repenning | 2002 | Theory development | Stock-and-Flow diagram | Aviation Safety | To highlights how catastrophic outcomes can be the result of an overaccumulation of mundane events and how the quantity of interruptions can push a system over its tipping point, rapidly degrading performance to the point that disaster is almost inevitable. |
| Taylor and Dangerfield | 2004 | Case study | Causal Loop and Stock-and-Flow diagrams | Healthcare (Patient Safety) | To analyse why managerial interventions in cardiac catheterisation services in the UK fail. |
| Cooke et al. | 2006 | Theory development | Causal Loop and Stock-and-Flow diagrams | Disasters (Industrial Safety) | To explore dynamics of the incident learning system, thereby motivating managers to introduce incident learning systems as a solution to move safety performance from normal accidents to high reliability. |
| Tang | 2007 | Case study | Stock-and-Flow diagram | Government (Software System Safety) | To analyse the risks and interrelationships of an e-government system. |
| Ulrey and Shakarian | 2008 | Case study | Stock-and-Flow diagram | Aviation Safety | To assess the impact of novel technology on safety and capacity of operations showing that reductions in either reporting interval length and/or control loop delay time resulted in increased safety and throughput levels. |
| Topolšek and Lipičnik, | 2009 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Traffic Safety | To reduce the number of motorway accidents due to wrong-way driving. |
| Xian-gong et al. | 2009 | Case study | Stock-and-Flow diagram | Coal Mine Safety | To analyse kinds of hazards and unsafe behaviour of employees in coal mine accidents in China from organisational and management perspective. |
| Mohamed and Chinda | 2011 | Theory development | Causal Loop and Stock-and-Flow diagrams | Construction Safety | To examine the relations amongst enables of construction safety culture and look at the potential effect of each enable on the organisational safety goals over a period of time. |
| Goh et al. | 2012a | Methodological development | Causal Loop diagram | Coal Mine Safety | To look at the dynamic relations between management of protection and production which has the potential effect to turn into an organisational accident. |
| Goh et al. | 2012b | Case study | Causal Loop diagram | Coal Mine Safety | To analyse accident prevention to assist in better understanding the causal influences of OHS performance. |
| Bouloiz et al. | 2013 | Theory development | Causal Loop and Stock-and-Flow diagrams | Multi-Industry (Industrial Safety) | To assess the safety of a storage unit in Morocco by modelling various scenarios to improve the safety of the industrial system and implement managerial tools involving organisational, technical and human factors. |
| Goh et al. | 2013c | Policy analysis or problem-solving | Stock-and-Flow diagram | Traffic Safety | To provides a range of experimental scenarios that will help policy and decision-makers develop appropriate and suitable traffic safety policies. |

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|---|---|---|---|---|---|
| Orjuela et al. | 2015 | Case study | Causal Loop and Stock-and-Flow diagrams | Multi-Industry (Industrial Safety) | To study the dynamic behaviour between transport infrastructure and the food supply chain in the city of Bogota. |
| McClure et al. | 2015 | Policy analysis or problem-solving | Stock-and-Flow diagram | Healthcare (Public Health Safety) | To illustrate different relationships amongst land use, transport, population health, and economic development in order to contrast the effect of different baseline scenarios and use – transport policies, on the motor vehicle crash deaths and disability-adjusted life years lost. |
| Guo et al. | 2015 | Theory development | Causal Loop and Stock-and-Flow diagrams | Construction Safety | To develop eight construction safety archetypes and apply it to construction of safety management. |
| Wang et al. | 2016 | Case study | Causal Loop and Stock-and-Flow diagrams | Construction Safety | To explore the mechanism of risk migration that resulted from the relations between a contractor's technical and organisational systems. |
| Lu et al. | 2016 | Policy analysis/ problem solving | Causal Loop and Stock-and-Flow diagrams | Aviation Safety | To reveal the organisational mechanism involving complex dynamic interactions of accident causal factors (technical, organisational and human) within the area of aviation engineering. |
| Goh and Askar Ali | 2016 | Methodological development | Causal Loop diagram | Construction Safety | To simplify integration of safety management considerations into construction activity simulation. |
| Garbolino et al. | 2016 | Case Study | Causal Loop and Stock-and-Flow diagrams | Multi-Industry (Industrial Safety) | To propose a dynamic risk analysis and scenarios analysis method using both SD and risk analysis. |

### *5.2.2 Resource management*

Five papers implemented SD applications that look at *resource management* which encompasses the realm of organisational-level decision-making vis-à-vis the sharing and maintenance of organisational assets (see Table 8). Practically all the studies employed the quantitative aspect of the SD approach. Anderson et al. (1994)'s application of the SD quantitative aspect proved to be useful in evaluating various treatment programs designed to prevent mother-to-infant transmission of the HIV. It provided stakeholders with the ability to examine the effects of screening, treatment, transmission and seroprevalence rates amongst pregnant women on the costs and safety benefits of various prevention programs. It demonstrated that regimens that prevent or reduce perinatal transmission of HIV cannot be implemented because of cost issues.

**Table 8 3**Literature Review – Resource Management

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Anderson and Anderson | 1994 | Case study | Stock-and-Flow diagram | Healthcare (Patient Safety) | To evaluate death prevention methods of HIV-infected infants who die within seven years by screening and introducing treatment options for HIV-positive mothers and their newborns. |
| Xiao-yan and Jian-hua | 2010 | Case study | Stock-and-Flow diagram | Healthcare (Patient Safety) | To model a hospital emergency service supply chain by highlighting the risk of illness' aggravation patients face with no timely treatment. |
| Maryani et al. | 2015 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Construction Safety | To analyse occupational accidents in construction projects and suggest improvements in the supply chain to enhance the quality of workers. |

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|---|---|---|---|---|---|
| Chia et al. | 2015 | Policy analysis or problem-solving | Stock-and-Flow diagram | Nuclear Safety | To examine the complex factors surrounding nuclear energy development in Singapore by evaluating four critical aspects, namely political, social, economic and environmental aspects in various scenarios. |
| Turner et al. | 2016 | Case study | Causal Loop and Stock-and-Flow diagrams | Disaster (Flood Safety) | To explore the potential trade-offs between the use of existing and new infrastructure; water and food risk security and the accompanying cost implications. |

*5.2.3 Organisational process*

Five papers looked at the *organisational process* which affects the organisational decisions and rules that govern the everyday activities within the organisation (see Table 9). One paper applied the qualitative SD approach only, and the other four papers applied the quantitative SD approach or both. In the first two papers, the SD proved to be useful for healthcare professionals to make decisions on health care priorities based on system analysis. Lane et al. (2000) developed an SD quantitative model that shows the relation between long waiting times in A&E and bed closures. The key finding of this model is that the major impact of bed shortages is not on emergency admissions, but was felt first on elective admissions so that using A&E waiting times to measure the effect of bed shortages is misleading. Gonzalez et al. (2016) discussed how a set of vicious feedback loops caused by following standard organisational procedures that do not fit the disaster situation, initially increases errors in response. Eventually, learning and sense-making in an improvisation/experimentation process lead to new emergent dynamics whereby the loops act virtuously. Lane at al. (2000) and Gonzalez et al. (2016) findings stress that more emphasis needs to be placed on system analysis and understanding the behavioural structure of key elements within the system that might not seem related at first glance.

**Table 9 4**Literature Review – Organisational Process

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Lane et al. | 2000 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Healthcare (Patient Safety) | To showcase the interaction of demand pattern, A&E resource deployment, and other hospital processes and bed numbers, allowing decision makers to base their decisions on systemic analysis to improve healthcare quality and safety. |
| Lattimer et al. | 2004 | Case study | Causal Loop and Stock-and-Flow diagrams | Healthcare (Patient Safety) | To investigate the scenarios for changing in terms of patient flows and bottlenecks and ways to intervene to ameliorate the worst-case scenarios. |
| Mohaghegh et al. | 2009 | Methodological development | Stock-and-Flow diagram | Aviation Safety | To investigate safety within the aviation by looking at the error probability of technicians over a period of 15 years as well as predicting management's commitment to safety. |
| Du and Zhang | 2015 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Aviation Safety | To demonstrate the interactions between flight safety and safety investment so that the optimal safety investment program can be determined in order improve level of flight safety. |
| Gonzalez et al. | 2016 | Policy analysis or problem-solving | Causal Loop diagram | Disaster (Landslide Safety) | To present large-scale disaster response of dissimilar types and what type of controls, such as training and policies, are available to reduce the vicious loops and speed the transition from errors to successful innovation |

### *5.3. Unsafe Supervisions*

Seven articles identified have applied SD approach to the safety policy at the management level.

#### *5.3.1 Inadequate supervision*

Five papers employed SD methodology that looks at *inadequate supervisions* in safety (see Table 10). One paper applied the qualitative SD approach only, and the other four papers applied the quantitative approach or both. A significant portion of the papers used case studies involving major accidents and examined how the SD approach can provide additional insight into the causes of these accidents. Salge et al. (2006) developed two separate SD models to illustrate that the Chernobyl accident was caused by a combination of human failure in the design of the reactor and poor decision-making. They argued that people could be blamed for those who design risk generating structures and those who react to failures in ways that increase the problem. They concluded that individuals who are aware of high-risk situations and wish to repair them would quite often behave in ways that will worsen the situation. Cooke (2003) examines the condition that led to the fatal explosion at the Westray mine in Canada using the SD approach. By providing valuable insights into the behaviour of the Westray mine disaster, Cooke argues that commitment to safety cannot be affected by production pressure. Consequently, he concludes that reduction in management commitment to safety can trigger a vicious cycle of frequent incidents, increase in production losses and pressure, and a further decrease in management commitment to safety.

Minami & Madnick (2009) used an SD approach to look beyond the human error in combat vehicle accidents and studied the organisational problems that were regarded as the real causes. They argued that with the short period efforts aiming to impose safety behaviours of combat soldiers will, in the long run, boost tiredness, fatigue and complacency. This, in turn, would destroy the primary safety policy and consequently recommended that understanding the dynamic effect various delays would yield has the greatest potential for improving safety.

**Table 10 5**Literature Review – Inadequate Supervision

| **Researchers** | **Year** | **Type of study** | **System Dynamics Tool** | **Industry** | **Purpose of SD Application** |
|---|---|---|---|---|---|
| Cooke | 2003 | Case study | Causal Loop and Stock-and-Flow diagrams | Coal Mine Safety | To examine the contributing factors of the Westray mine disaster, including interactions that could have led to the conditions that triggered the fatal explosion at the mine. |
| Simonovic and Ahmad | 2005 | Case study | Causal Loop and Stock-and-Flow diagrams | Disaster (Flood Safety) | To assess the effectiveness of different flood evacuation policies thereby contributing to a higher quality of decisions and a higher level of emergency preparedness. |
| Salge and Milling | 2006 | Case study | Causal Loop and Stock-and-Flow diagrams | Nuclear Safety | To analyse the accident at the Chernobyl power plant by looking at the human failures in two stages: planning and design of the socio-technical-environment and online operations. |
| Minami & Madnick | 2009 | Case study | Causal Loop diagram | Military Safety | To study the upper-level organisational processes and complications that constitute the root causes of accidents instead of focusing on symptoms and events of accidents which normally specify human error. |
| Wu and Xie | 2012 | Theory development | Stock-and-Flow diagram | Railway Safety | To enhance emergency safety decision-making efficiency in railway management. |

*5.3.2 Planned inappropriate operations*

Two papers looked at *planned inappropriate operations* of which supervision fails to adequately assess the hazards (see Table 11). Both papers developed qualitative models and converted it to quantitative simulation models in order to understand the factors affecting delay within the system. Min et al. (2011) assessed the behaviour of disaster-relief supply chain under adverse conditions. Akkermans and Van Oorschot (2016) modelled a major new aircraft development based on inputs from the industry. The results suggested that major improvements occur when more concurrency is allowed because, in projects of such complexity, concurrent team learning is crucial.

**Table 11 6**Literature Review – Planned Inappropriate Operations

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Min and Hong | 2011 | Case study | Causal Loop and Stock-and-Flow diagrams | Disaster Relief Safety | To analyse impacts of delay to the disaster-relief system by studying several scenarios to improve decision-making. |
| Akkermans and Van Oorschot | 2016 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Aviation Safety | To illustrate that less concurrency can contribute to overall project delays, rather than preventing them. |

*5.4. Preconditions for Unsafe Acts*

Eighteen SD applications have been identified that utilised the SD approach to look at safety in the work environment. These include *environmental factors, the condition of the operator and personnel factors*.

*5.4.1 Physical and technical environment factors*

Seven papers applied SD simulation to look at the *physical and technical environmental factors* (see Table 12). Majority of the papers addressed issues concerning road traffic safety as well as nuclear safety. Chong et al. (2015) investigated the trade-offs of various quality and safety outcomes in an emergency department to assess the efficiency of healthcare systems. Similiarly, Rong et al. (2016) modelled the interrelationships amongst the factors in missile operations which may contribute to accidents. The long-term behaviour of a socio-technical system with several human operations under the given conditions is clearly reflected in this temporal uncertainty analysis, which enables people to examine the possible trade-offs between short-term profits and sustainable long-term improvement. Woo (2015) was able to characterise power uprates in nuclear power plants and found that the cost of nuclear power plants can be minimised through risk assessment which can also help to avert unexpected disasters and increase their safety level.

**Table 12 7**Literature Review – Physical and Technical Environment Factors

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Mehmood et al. | 2003 | Policy analysis or problem-solving | Stock-and-Flow diagram | Traffic Safety | To addresses the shortcomings of previous car-following models and how that contributes to traffic safety. |
| Zhang et al. | 2008 | Case study | Stock-and-Flow | Traffic | To elevate safety level of traffic accident scene and which factors |

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|---|---|---|---|---|---|
| | | | diagram | Safety | predominately influence it. |
| Woo | 2015 | Policy analysis or problem-solving | Causal Loop and Stock-and-Flow diagrams | Nuclear Safety | To analyse the economic and safety properties of power increases in nuclear power plants |
| Chong et al. | 2015 | Case study | Causal Loop and Stock-and-Flow diagrams | Healthcare (Patient Safety) | To study the trade-offs of various quality and safety results in an emergency department in order to assess the efficiency of healthcare systems. . |
| Rong et al. | 2016 | Case study | Causal Loop and Stock-and-Flow diagrams | Nuclear Safety | To analyse the Minuteman III missile accident in 2008 that looks at the interrelationships amongst technical and organisational aspects. |
| Koh et al. | 2016 | Policy analysis or problem-solving | Stock-and-Flow diagram | Traffic Safety | To model human driving characteristics and driving patterns and simulate various types of driver behaviours |
| Yan et al. | 2016 | Case study | Causal Loop and Stock-and-Flow diagrams | Railway Safety | To analyse the typical cases of subway fires over past 20 years, highlighting the causes of the fire accidents and extracting influencing factors such as equipment, human, environment and emergency management. |

### *5.4.2 Condition of operators*

Nine papers employed SD methodology to address the conditions of individuals that can have the adverse influence on their job performance (see Table 13). Majority of the papers addressed safety issues within the healthcare. Homer (1984) applied the qualitative SD to explore the dynamics of "worker burnout" and demonstrate the potential effectiveness of stabilising techniques that can diminish work-related stress or enhance relaxation which in turn increases overall productivity. The author showed that the individual can effectively manage the self-inflicted nature of burnout. Similarly, Oliva (2001) modelled responses to work-related pressure in service industries and simulated the impacts of increased level of working, cutting corners, lowering standards and expectations which delay the resourcing of additionally required capacity. He illustrated how this is particularly challenging in healthcare, where high professionalism and lengthy training times make the situation considerably worse in comparison to other industries. McDonnell (2005) modelled interactions amongst the key determinants of medication errors, in particular, the complex interactions of patients and staff, information, medications, work practices and the infrastructure and policies within a hospital environment. Rashwan and Arisha (2015) examined a clinical unit in a large hospital in Ireland in order to simulate the impact of nurses' behaviours at their burnout level on unit performance measures. Working with the nurses and the management team of the unit, the authors developed an SD model to encompass the factors that may contribute to the burnout phenomenon and also the relationship between these factors and the performance measures.

**Table 13 8**Literature Review – Condition of Operators

| Researchers | Year | Type of study | System Dynamics Tool | Industry | Purpose of SD Application |
|---|---|---|---|---|---|
| Homer | 1984 | Policy analysis or problem-solving | Causal Loop diagram | Healthcare (Patient Safety) | To explore the dynamics of worker burnout. |
| Oliva | 2001 | Policy analysis or problem-solving | Stock-and-Flow diagram | Multi-Industry (Industrial Safety) | To highlight the trade-offs in responses to work pressure in the service industry and how that affects stress and burnout. |

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|---|---|---|---|---|---|
| McDonnell | 2005 | Policy analysis or problem-solving | Stock-and-Flow diagram | Healthcare (Patient Safety) | To represents the interactions amongst the key determinants such as everyday clinical work amongst patients and staff that deliver medications safely. |
| Morris et al. | 2010 | Theory development | Causal Loop diagram | Healthcare (Patient Safety) | To measure vague human factors variables such as stress in a way that is understandable, computable, robust and capable of being validated. |
| Guo et al. | 2013 | Methodological development | Causal Loop diagram | Healthcare (Patient Safety) | To identify the relationship between schedule and quality performances and the components related to a safety program and how that impacts safety management in practice. |
| Han et al. | 2014 | Case study | Causal Loop diagram | Construction Safety | To look at the causation of unsafe behaviours in Construction. |
| Shin et al. | 2014 | Theory development | Stock-and-Flow diagram | Construction Safety | To quantify fuzzy human factors variables such as stress in a way that is robust, computable, understandable, and capable of being validated. |
| Rashwan and Arisha | 2015 | Policy analysis or problem-solving | Stock-and-Flow diagram | Healthcare (Patient Safety) | To identify factors affecting nurses' behaviour when they experience burnout level and its impact on patients' experience time. |
| Da | 2016 | Policy analysis/ problem solving | Causal Loop and Stock-and-Flow diagrams | Railway Safety | To examine the influence of railway workers' mental processes and on safety attitudes and safe behaviour. |

*5.4.3. Personal factors*

Two papers developed SD models that addressed the *personal factors within the work environment* (see Table 14). Wei et al. (2012) modelled the problems of human errors in the aircraft cockpit and discovered that a systems modelling approach can make mid or long-term prediction of the prevention level of human errors in civil aviation incidents. Carhart (2010; 2009) adopted SD group model building using Causal Loop Diagrams (CLDs) as a tool for event investigation in the nuclear industry and demonstrated that CLDs can provide additional insights into the development of an event. Both papers showed the potential of the SD approach for proactively predicting system behaviour/failure.

**Table 14 9**Literature Review – Personal Factors

| **Researchers** | **Year** | **Type of study** | **System Dynamics Tool** | **Industry** | **Purpose of SD Application** |
|---|---|---|---|---|---|
| Carhart | 2009 | Methodological development | Causal Loop and Stock-and-Flow diagrams | Nuclear Safety | To promote systems-thinking methodology in analysing incident causality and the investigation process for proactive hazard analysis programme. |
| Wei et al. | 2012 | Methodological development | Stock-and-Flow diagram | Aviation Safety | To simulate human error analysis of human cockpit errors and how it can be reduced. |

*5.5. Unsafe Acts*

Three SD applications have been identified that look at the *unsafe acts* (operator level) including *decision, skill-based and perceptual human errors and violation*s (see Table 15). Jiang et al. (2015) and Nakumura et al. (2015) constructed quantitative simulation models that look at unsafe behaviours of marine engineers and construction workers respectively. Jiang et al. (2015) built upon Shin's (2014) previous work by introducing an SD model for the causation of unsafe behaviours based on a holistic cognitive analysis of why unsafe behaviours happen. Through the simulation results, they reveal how construction workers can be better understood and how unsafe behaviours can be fundamentally prevented. Similarly, Nakumura et al. (2015) constructed a quantitative simulation model to comprehend how the behaviour pattern of engineers can contribute to marine accidents.

**Table 15** Literature Review –Unsafe Acts

| **Researchers** | **Year** | **Type of study** | **System Dynamics Tool** | **Industry** | **Purpose of SD Application** |
|---|---|---|---|---|---|
| Kontogiannis | 2011 | Policy analysis or problem-solving | Causal Loop diagram | Healthcare (Patient Safety) | To analyse and compare error recovery strategies regarding patterns of system affordances, interaction, and types of recovery plans, allowing safety experts to produce resilient system designs and training solutions for managing human errors in unforeseen situations. |
| Jiang et al. | 2015 | Policy analysis or problem-solving | Stock-and-Flow diagram | Construction Safety | To develop construction workers' mental process that can help analyse the feedback mechanisms and the resultant dynamics vis-à-vis the workers' safety attitudes and safe behaviours. |
| Nakamura et al. | 2015 | Policy analysis or problem-solving | Stock-and-Flow diagram | Maritime Safety | To investigate characteristics of human errors in marine accidents by analysing latent factors and onshore management personnel |

## 6. Discussion

This paper aims to examine the connection between safety improvement and SD by reviewing literature that attempts to improve system safety in complex systems by utilising SD modelling. Based on the adopted safety framework, the extended HFACS, findings from the literature review were analysed and presented across five categories. We return here to discuss our findings with respect to the three research questions posed in section 1: what safety issues have been addressed by SD, how has SD been applied to improve system safety and how might SD be further applied to system safety?

### *6.1 What safety issues have been addressed by SD?*

SD was applied to address most of issues in the extended HFACS framework. The most interesting finding is that organisational influences, more specifically speaking, organisational climate, was the most dominant issue to which SD was applied. It proves that SD is instrumental in analysing complex socio-technical issues in the working environment within the organisation which includes culture, policies and structure. Not surprisingly, organisational climate is linked with safety climate, so SD can be further utilised as a tool for studying dynamic interaction between safety climate/culture and various aspects in the subsequent tiers (supervision quality, working conditions and acts). The second most frequent use of SD was to address unsafe supervision, concentrating on the issue of inadequate supervision. It is defined as a factor in a mishap when supervision has failed to identify a hazard, recognise and control risk, provide guidance, training and/or oversight, and results in human error or an unsafe situation (Force, 2005). Much of the literature argues that lack of a solid communication between the workers and management causes management to forgo safety in order to promote production pressure, making way for potential unsafe acts to occur which are ultimately blamed on the sharp end. Much of the identified studies looked at the conditions of the operators as well as decision-based, skill-based and perception-based errors that they generate. The themes that keep repeating are solutions on how to reduce human errors by modelling high workload and fatigue and its interactions with the rest of the tiers. Only one SD application (2005) has encompassed over four tiers (Organisational influences, Unsafe supervisions, Preconditions for unsafe acts and Unsafe acts), revealing a glaring gap and future potential to develop further SD applications that cross across multiple tiers.SD has been utilised for both retrospective analysis (accident analysis) and prospective analysis (policy analysis). Approximately half of the studies were accident case studies where SD was utilised for accident investigation. Cooke (2003) for instance utilised SD to describe lessons learned from the Westray mining accident of 1992 in which a number of miners lost their lives. His SD model provided a useful means for identifying underlying causes with dynamic considerations. Nearly a quarter of the studies were SD applications that provide problem-solving or policy analysis. Topolšek et al. (2009) investigated why there was an increased number of traffic accidents based on wrong-way driving and highlighted intervention strategies and countermeasures to reduce it. The third most frequent type of study was theory development. One standard usage is reflected in Shin et al. (2014)’s paper where they used SD to capture construction workers' mental process to analyse the feedback mechanism and the resultant dynamics regarding the workers' safety attitudes and safety behaviours. The least common type of study was methodological development. Practically all the literature for methodological development were published nine years, perhaps an indication that there is a new drive to utilise SD to improve and address issues in system safety. An example of methodological development is Goh et al. (2012b) who focused on modelling and providing analysis between management of production and production whilst addressing an existing gap. Consequently, SD modelling seems to be more applicable when developed for accident case studies and problem-solving/policy analysis as the literature shows.

*6.2 How has SD been applied to improve system safety?*

The second question explores how SD has been applied to improve system safety. Based on the existing literature, SD has been successfully applied to address several safety issues in many different ways: i) proactively preventing incidents; ii) group learning; iii) testing out potential policy impacts on safety. Mental models of the factors that promote accidents were created by Cooke et al. (2006) who also tested the viability of potential methods for their prevention. Similarly, employing the SD approach, Shin *et al*. (2014) modelled the mental process factors behind the unsafe activities of construction workers. Several interventions for promoting safe behaviours and improving safety-related communications were evaluated by the authors who also demonstrated the suitability of this model as an expressive tool (i.e. a shared mental model). In a different light, the issue of misuse of personal protective equipment (PPE) among pesticide applicators was investigated by Feola et al. (2012) who examined how different inventions could be applied to minimise this problem of PPE mismanagement. SD has been utilised as an effective strategy for enhanced learning where one application introduced an organisational response system in which precursor events, or safety-related incidents, are used as the basis for training and planning to combat organisational complacency and promote effective learning  For policy impacts on safety, Leveson (2012) devised a model that shows the efficacy of the safety policies when new pharmaceutical drugs are introduced.

Not surprisingly, over a third of the identified SD applications are used in healthcare domain, and this is consistent with the increasing usage of SD in healthcare in contrast to other industries over the past decade (Brailsford, 2008). Homer et al. (2006) argue that SD modelling is the perfect candidate to address the dynamic complexity that characterises many public health issues.

*6.3 How might SD be further applied to system safety?*

The third question explores how SD might be further applied to system safety. The implementation of SD implies capturing the complexity of social reality by developing models based on the mentality of the different individuals involved in a system, so as to interpret or define a phenomenon or problem (Lane and Oliva, 1998). It allows critical issues to be explored from different perspectives, which enables the modeller to have access to insights and changes relating to alternative techniques as well as to compare the outcomes of various scenarios generated from simulation (Lane and Oliva, 1998).

The results of both theoretical and practical implementations suggest that SD has the potential to improve safety in a variety of sectors but is underused. It could produce deep learning with a dynamic and contextual appreciation not provided by the current models and tools. Moreover, there seems to be a lack of applied system dynamic models in safety-critical industries where trade-offs are used all the time. SD has the potential to provide a balancing and strategic learning output in determining the most optimal trade-off. With increasingly complex systems being built, useful tools are needed that allow us to understand their complexity, design better safety policies and guide effective change. SD has the potential to provide and implement enhanced learning for safety, and it continues to be a contender as a sophisticated management decision support tool for complex systems. Decision makers can benefit from virtual scenario testing within a safe simulation environment so that impacts on policy adjustments can be immediately visualised.

A number of studies (Goh et al., 2012a; Han et al., 2014; Lattimer et al., 2004; Taylor and Dangerfield, 2004) argue that the SD approach has the potential to be applicable in related areas with slight modifications. Some others mentioned that fine-tuning is necessary based on continuous feedback from stakeholders (Simonovic and Ahmad, 2005). Others have argued that given limited time and resources, the qualitative aspect of SD can be a potential tool to elicit insights and enable learning (Carhart, 2009). Goh et al. (2012b) argue that SD modelling should not be considered as a complete replacement or substitute for existing approaches but should be utilised as part of a complementary tool. This is similarly echoed by Wang et al.

(2013) and Jiang et al. (2015) who argue that since SD studies high-level effects at an aggregate level, individual differences and data outliers are lost. As a result, having supplementary modelling approaches is beneficial to understand system complexity.

In comparison with the existing accident risk analysis models such as Rasmussen's Risk Management Framework, STAMP, FRAM, and HFACS, SD has the potential to cover the limitations accompanying those frameworks as it can enhance our understanding of the dynamic behaviour of systems in both qualitative and quantitative aspects. The existing frameworks tend to be qualitative and static in nature, but safety is never a static quality that can be achieved because systems are always moving to states of high risk (Dulac, 2007).

SD enables the behaviour of the system (and its subsystems) to be both represented and simulated. Its simulation capability allows changes such as technical or organisational safety means to be tested to evaluate their potential effectiveness prior to implementation. Changes can be introduced in either the design or the operation phase. As a result, it can form part of a continuous improvement strategy for the prevention and management of safety issues.

The SD framework incorporates delay which can be used to understand the dynamic effect of various time delays in the system. Understanding and using delays can be significant for implementing effective long-term safety measures in lieu of short-term actions. Delays also help understand the impact of unintended side-effects arising from short-term safety measures and also a result, efforts can be made to mitigate its impacts (Minami et al., 2010; Xian-gong et al., 2009).

The SD tool can also be used to generate insights through behavioural archetypes which can visualise complex phenomena. Causal loop diagrams can be used to identify emerging problems proactively rather than having to resort to event-level interventions (Goh et al., 2010). When the systemic structure is better understood, intervention points to improve and sustain safety culture can be identified (Goh et al., 2010). As has been previously demonstrated (Senge, 1990) causal loop diagrams can be sufficient for communicating behavioural archetypes to improve safety.

Unlike existing safety frameworks, SD provides a unique process of participation and model building that gives an insight into the causes of accidents. The participants can be better understood through active investigation and retrospective learning. A safety culture is usually developed through constant learning and examination of these events in various industries. Safety also deals with the ability of a system, especially complex socio-technical systems prone to high impact and low probability events, to react to new and unique developments as well as to keep track of existing processes. A lot of investigations have been carried out on the importance and nature of learning in safety-critical domains. Learning within the organisations was identified by several authors to be disjointed and basically focused on the local process whilst neglecting the deep learning stage of the underlying processes (Carroll et al., 2002; Huber et al., 2009). It is believed that this deep learning can be obtained from systems models. It is not enough to rehearse emergency plans and ensure they have been learnt (Lagadec, 1997). Effective deep learning is needed in order to prepare for these unique developments, and this deep learning is provided by the participatory model building of causal loop diagrams and SD models for prospective and external events as well as internal investigations.

It is important to point out that not all potential consequences of a decision can be conveyed by the SD framework. In addition, it is not capable accurately and wholly predicting the nature and effect of all factors endogenous to the system. However, it provides the option to conduct numerous, iterative test-runs of the safety performance of a system in operationally relevant scenarios. This gives stakeholders the access to relevant information pertaining the probabilities of various adverse consequences as well as possible means of eliminating unanticipated and unintended consequences.

In short, the application of SD as a system safety enhancement technique will enable researchers and decision makers to understand how changes in the structural and dynamic properties of a system can influence its current and future behaviours. This allows them to identify safety improvements as well as adverse consequences.

## 7. Conclusion and Future Challenges

This paper aims to examine the connection between safety and SD by reviewing literature that attempted to improve system safety in complex systems by utilising SD modelling. A literature search and thematic analysis of empirical literature addressing SD application in safety-critical domains was conducted. The findings were categorised based on a modified safety framework that we entitled HFACS-EE.

Simulation has mainly been used in system safety as an instrument for predicting system behaviour, testing model structures, testing different techniques as well as analysing various scenarios as revealed by the literature reviewed in this research. In view of the results obtained, the authors were able to improve safety through greater decision-making by including past behavioural events in modelling structures to create effective safety policies, performing system analysis as well as applying a holistic approach to analyse the causes of accidents beyond human error. In circumstances where the actions, omissions, communications or policies of top management directly or indirectly affect supervisory practices, actions or conditions of the operator(s) and lead to human error, stem failure or an unsafe situation, SD has often been used as a tool to pinpoint the factors responsible for accidents.

The future adoption of the SD approach in the field of system safety basically depends on various factors such as creating more awareness about the feasibility of the SD methodology and applying it in practical safety scenarios

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**Appendix A. HFACS**

*A.1. Brief description of HFACS-EE causal categories*

| | | |
|---|---|---|
| **External Factors** | Regulatory Factors | The effects that government adopted laws, regulations and policies have on the organisation. It includes how actions of the regulator, including inspections and enforcement, affect safety. The formulation to control over hazardous processes. |
| | Others | The effect society as a whole has on the safety including economic pressure, environmental concerns and legal pressure |
| **Organisational Influences** | Organisational climate | The working atmosphere within the organisation which includes culture, policies and structure |
| | Operational process | This refers to organisational decisions and rules that govern the everyday activities within the organisation. This includes the establishment/use of standard operational procedures, and formal methods for maintaining oversight of the workforce. |
| | Resource management | This encompassess organisational-level decision-making vis-à-vis the sharing and maintenance of organisational assets (such as personnel, money, equipment and facilities) |
| **Unsafe supervisions** | Inadequate supervision | The factors that supervision fails to identify a hazard, recognise and control risk, provide guidance, training and/or oversight, etc., resulting in human error or an unsafe situation |
| | Planned inappropriate operations | The factors that supervision fails to adequately assess the hazards associated with an operation and allow for unnecessary risks |
| | Failed to correct problems | The factors that supervision fails to correct known deficiencies in documents, processes or procedures, or fails to correct inappropriate or unsafe actions of individuals create an unsafe situation |
| **Preconditions for unsafe acts** | Environmental factors | This category encompasses a variety issues, including the design of equipment and controls, display/interface characteristics, checklist layout, task factors and automation. It also includes the operational setting (e.g. weather, altitude, terrain) and the ambient environment (e.g., heat, vibration, lighting, toxins) |
| | Condition of the operator | The conditions of an individual that can have adverse influence to perform his/her job such as mental fatigue resulting from high work-load, pernicious attitudes, and misplaced motivation. This also includes mental/physical limitations of the practitioners. |
| | Personnel factors | Includes a variety of communication, coordination, and teamwork issues that impact performance |

| | | |
|---|---|---|
| **Unsafe acts** | Human errors | *Decision errors:* These “thinking” errors represent conscious, goal-intended behaviour that proceeds as designed, yet the plan proves inadequate or inappropriate for the situation. These errors typically manifest as poorly executed procedures, improper choices, or simply the misinterpretation and/or misuse of relevant information.<br>*Skill-based errors:* Highly practiced behaviour that occurs with little or no conscious thought. These “doing” errors frequently appear as breakdown in visual scan patterns, forgotten intentions, and omitted items in checklists. Even the manner or technique with which one performs a task is included.<br>*Perceptual errors:* Medication errors resulting from sound alike, look-alike drugs or the use of decimal point or abbreviations |
| | Violations | *Routine violations:* Often referred to as “bending the rules,” this type of violation tends to be habitual by nature and is often enabled by a system of supervision and management that tolerates such departures from the rules.<br>*Exceptional violations*: Isolated departures from authority, neither typical of the individual nor condoned by management |